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Effectiveness of Interactive Learning Media Based on Virtual Laboratory on Scientific Literacy and Concept Mastery in Dynamic Electricity

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Abstract: Scientific literacy is an individual's ability to apply scientific knowledge, identify questions, and draw conclusions based on evidence to understand and make informed decisions about the natural world and changes resulting from human activities. This study aims to analyze the effectiveness of interactive learning media based on the Virtual Laboratory in enhancing scientific literacy and improving students' conceptual understanding of the Dynamic Electricity. The study employed a quasi-experimental design, specifically the One-Group Pretest–Posttest Design, without a control group. The research subjects consisted of four ninth-grade students from two schools, namely SMPN 3 Pagimana and SMPN 5 Pagimana, totaling 80 students. The research instruments consisted of a science literacy test and a concept mastery test, each consisting of 10 essay questions and validated by experts. The results showed that the use of Virtual Laboratory media effectively improved students' science literacy, as indicated by a significant increase in scores on the posttest compared to the pretest. Statistical analysis using a paired sample t-test yielded a significance value < 0.05 in all classes, indicating a meaningful difference between students' initial and final abilities. Furthermore, the Normalized Gain (N-gain) value was in the high category (0.93–0.97). Thus, interactive learning media based on Virtual Laboratories have proven effective in improving students' science literacy and concept mastery of the Dynamic Electricity, and can serve as an alternative solution in science learning in schools with limited laboratory facilities.

Keywords: Concept mastery; Dynamic electricity; Learning media; Scientific literacy; Virtual laboratory

Introduction

The development of human thought in defining the meaning and understanding of education always shows changes. These changes are based on various findings and changes in the field related to the increasing number of components of the existing education system (Ainscow et al., 2019; Yurkofsky et al., 2020). The development of mindsets among educational experts, administrators, and observers has led to the emergence of new theories and perspectives. Advances in technological tools have also contributed to the changes in the meaning and understanding of education. At the same time, the learning and educational process is always ongoing and continues. Therefore, it is possible that an educational perspective always exists and continues (Pambudi & Harjanto, 2020; Wang et al., 2024; Guàrdia et al., 2021). The preamble to the 1945 Constitution states that one of the goals of the Republic of Indonesia is to educate the nation, regardless of any individual, through quality education tailored to their interests and talents. Quality education is a prerequisite for the availability of qualified human resources competent in science and technology (Wahyudin & Suwirta, 2020; Qutni et al., 2021).

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In today's global era, the rapid development of information and communication technology, particularly the internet, is crucial. An education system must be responsive to the dynamics of change occurring in various areas of national life (Chatterjee & Chakraborty, 2021; Tiwari & Fahrudin, 2024). Education today requires a modern and professional approach, utilizing technological advances to enhance flexibility and improve the quality of education, bringing about significant changes (Whalley et al., 2021; Qureshi et al., 2021).

The development of information and communication technology has driven a significant transformation in the world of education. One impact is the emergence of various digital learning media that offer high flexibility and interactivity (Wang et al., 2024; Alam & Mohanty, 2023). Amidst the demands of the Industrial Revolution 4.0 and the 21st-century learning era, students are required not only to master scientific concepts but also to possess strong scientific literacy skills, enabling them to think critically and analytically, and make informed decisions based on scientific data. Natural Science is one of the core subjects in the Indonesian education curriculum, including at the junior high school level (Indriani et al., 2021; Varlık, 2025; Permanasari et al., 2021).

Science learning cannot be achieved through memorization or passively listening to teacher explanations; students must learn through active experimentation and observation. This ultimately fosters creativity and fosters awareness and improvement of natural phenomena (Jamil et al., 2021; López et al., 2024). This encourages a scientific attitude, which in turn actively strives to maintain the stability of nature in a manner that is both appropriate and sustainable. Science learning is crucial because students can discover and prove scientific theories themselves. These theories are learned through direct inquiry, both in the laboratory and in the environment, thereby developing and enhancing students' scientific process skills (Etkina et al., 2020; Susilawati & Sridana, 2015; Chengere et al., 2025).

Several obstacles frequently encountered in science learning, including practical activities, include inadequate supporting facilities and a lack of proper materials (Kamba et al., 2019). Another obstacle encountered during classroom learning is that some students prefer kinesthetic learning styles, others prefer audio-based learning, and still others prefer visual learning media (Vas & Sharma, 2025). Kinesthetic learners prefer physical movement to retain information. Students who prefer audio-based learning utilize their sense of hearing to absorb the material being explained. In contrast, those who prefer visual learning can learn optimally through their sense of sight (Bryant, 2023; Desagon et al., 2025; Ha & Im, 2020).

Virtual laboratories provide a simulated experience that allows students to conduct experiments digitally, without the constraints of time and space. This medium is capable of increasing student engagement, visualizing abstract concepts, and supporting the achievement of 21st-century competencies such as problem-solving, collaboration, and digital literacy. Several recent studies suggest that the use of virtual laboratories in science education has the potential to enhance students' understanding of scientific concepts and literacy significantly (Durkaya, 2023; Yurchenko, 2025; Putri et al., 2021; Asare et al., 2023).

Scientific literacy is an individual's ability to apply scientific knowledge, identify questions, and draw conclusions based on evidence to understand and make informed decisions about the natural world and changes resulting from human activities. Scientific literacy encompasses not only content comprehension but also dimensions of scientific processes and attitudes, such as critical thinking skills, evaluating evidence-based information, and engaging in science-based social issues (Sutiani, 2021; Aristeidou & Herodotou, 2020; Schwartz et al., 2023).

Meanwhile, conceptual mastery refers to students' ability to understand, explain, and apply basic scientific concepts correctly (Dewi et al., 2020). This includes an understanding of scientific principles, laws, and theories, as well as the ability to relate them to observed phenomena. Conceptual mastery forms the basis for systematic thinking, solving scientific problems, and developing a comprehensive understanding of the physical and biological world. Students with strong conceptual mastery are better able to solve problems based on understanding, rather than simply memorizing (Amanda et al., 2022; Harjono et al., 2020).

Recent studies have shown that virtual laboratories, as an interactive learning medium, have proven effective in improving both competencies. For example, Putri et al. (2021) found significant improvements in scientific literacy through inquiry-based virtual laboratory activities on the topics of light and optics. A systematic review by Rosli & Ishak (2024) also confirmed that integrating virtual labs into science education can improve students' learning outcomes and practical competencies. Furthermore, research by Ismail et al. (2016) demonstrated that STEM-based virtual labs led to moderate improvements in the N-gain of junior high school students' scientific literacy.

Results of national and international surveys, such as the Programme for International Student Assessment (PISA), indicate that Indonesian students' scientific literacy remains low. Furthermore, limited laboratory infrastructure in many schools is a barrier to effective and meaningful science learning. In this context, utilizing virtual laboratories as an interactive learning medium is a strategic alternative to overcome the limitations of conventional laboratories (OECD, 2022). Indonesian students have low levels of scientific literacy for several reasons, including teacher-centered learning, negative student attitudes toward science learning, and a lack of fundamental understanding of the content, processes, and context. Consequently, lessons become boring and students struggle to understand them (Sholahuddin et al., 2021). One cause of poor mastery of scientific concepts and literacy is a learning approach that lacks depth, theoretical focus, and limited hands-on experience. In many schools, limited laboratory facilities and teaching resources are significant obstacles to providing contextual and exploratory science learning (Schwartz et al., 2023; Akerson & Bartels, 2023).

Based on the above discussion, the author proposes a solution in the form of various technology-based learning innovations that have been developed, one of which is the use of virtual laboratories. This learning medium enables students to conduct interactive, safe, and flexible experimental simulations at any time and from anywhere. With virtual laboratories, students not only gain theoretical understanding but also experience the process of direct scientific inquiry: formulating hypotheses, testing variables, and analyzing data. This aligns with the demands of the independent curriculum, which emphasizes differentiated, collaborative, and project-based learning.

Method

This research was conducted at two schools: SMPN 3 Pagimana and SMPN 5 Pagimana, located in Banggai Regency, Central Sulawesi Province, in September and October 2025. This study employed a quasi-experimental design. The research design employed in this study was a One-Group, Pretest-Posttest Design. The flow scheme in this study is as follows: problem identification, literature review, instrument development and validation, pretest, treatment (virtual laboratory), posttest, data analysis, and finally, conclusions in research flow chart on Figure 1.

This study uses all subjects in the study group to receive treatment collectively, rather than randomly selecting subjects for treatment. Because this study aims to examine the effect of treatment on a group, it uses two experimental classes and two replication classes, without a control class. The replication class is intended to ensure the research results are robust and not obtained by chance. The treatment will be the implementation of interactive learning media based on a virtual laboratory. The population in this study is students at SMPN 3 Pagimana and SMPN 5 Pagimana, consisting of two ninth-grade students at SMPN 3 Pagimana and two ninth-grade students at SMPN 5 Pagimana, Classes IX A and IX B.

In the context of research, a sample refers to a subset of the population that is selected to represent the entire population in a study. Appropriate sample selection is crucial to ensure that research results are generalizable and have high validity. The data in this study are student learning outcomes. Data were collected using pretest and posttest techniques. The instrument used in this study was an essay-based test to measure conceptual mastery and scientific literacy. It was designed according to the indicators of conceptual mastery and scientific literacy. Student learning outcome data were analyzed using data normality tests, hypothesis tests, and the N-Gain test.

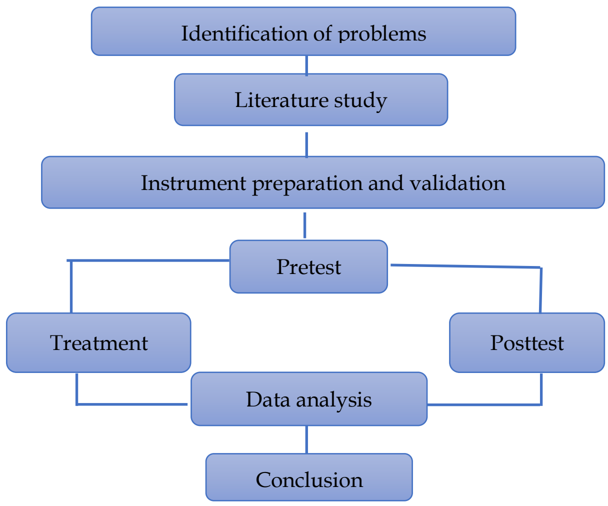

Figure 1. Research flow chart

Result and Discussion

The research, entitled "The Effectiveness of Interactive Learning Media Based on Virtual Laboratories on Scientific Literacy and Concept Mastery in Dynamic Electricity," collected Data on student learning outcomes after students received treatment using virtual laboratory learning media within a guided inquiry learning model. To measure student learning outcomes using normality tests, hypothesis tests, and n-gain tests.

Based on Figure 2, it can be seen that, before the pretest was administered, the average scores were 17 in Experimental 1, 10 in Experimental 2, 15 in Replication 1, and 16 in Replication 2. Furthermore, when virtual laboratory-based learning media were provided during the learning process, the average posttest scores were 94 in Experimental 1, 92 in Experimental 2, 95 in Replication 1, and 97 in Replication 2. This indicates that each class experienced an improvement. Furthermore, the pretest and posttest results for each respondent in Experimental 1, Experimental 2, Replication 1, and Replication 2 were analyzed.

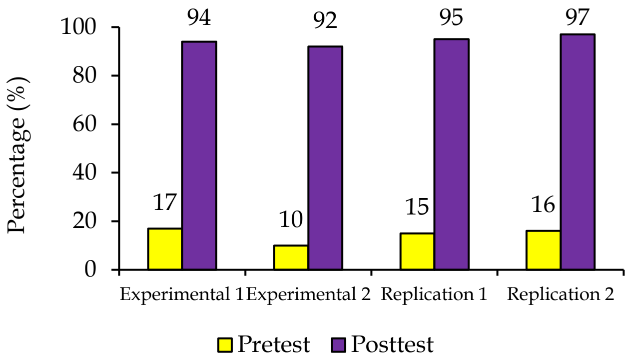

Figure 2. Improving student learning outcomes in experimental and replication classes

The results of the study indicate a significant increase in students' mastery of concepts and scientific literacy after the implementation of the Virtual Laboratory media. Based on Figure 2, all classes in this study demonstrated higher posttest scores than their pretest scores. This pattern of improvement aligns with the findings of Abdjul & Ntobuo (2019), who stated that the use of virtual laboratory media significantly contributes to enhancing conceptual understanding in science learning.

Through interaction with virtual simulations, students can conduct independent experiments, observe changes in variables in real time, and draw conclusions based on scientific evidence. Thus, the implementation of interactive PhET Simulation media has proven effective in strengthening students' conceptual mastery and learning outcomes in Dynamic Electricity. The following graph demonstrates the improvement in students' conceptual understanding in Figure 3 for average Mastery of Concepts of Experiment class and Figure 4 for Average Mastery of Concepts of Experiments replication class.

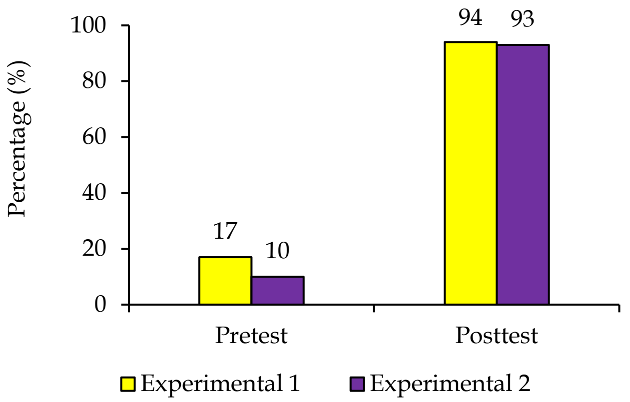

Figure 3. Average mastery of concepts of experiments 1 and 2

Based on the Figure 3, the average score for Experimental 1 before learning was 17, while for Experimental 2, it was 10. After implementing learning using virtual laboratory-based media with the help of PhET Simulation, the average post-test scores significantly increased, reaching 94 in Experimental 1 and 92 in Experimental 2. These data indicate an increase in conceptual mastery in both experimental classes at SMPN 3 Pagimana after being exposed to interactive virtual laboratory-based learning. This improvement demonstrates that the use of virtual laboratory media can improve conceptual mastery.

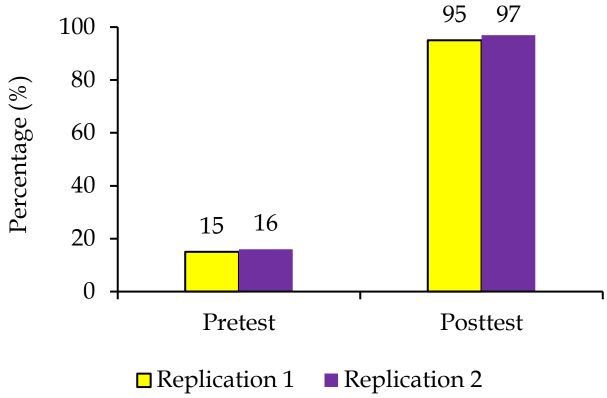

Figure 4. Average mastery of concepts of experiments replication 1 dan 2

Based on Figure 4, in replication 1, the average score before learning was 15, while in replication 2, it was 18. After implementing learning using virtual laboratory-based media with the help of phET Simulation, the average posttest scores significantly increased, reaching 95 in replication 1 and 97 in replication 2. These data indicate an increase in concept mastery in both replication classes at SMPN 5 Pagimana after being exposed to interactive virtual laboratory-based learning. This improvement demonstrates that the use of virtual laboratory media can improve concept mastery. This means that all four classes experienced significant improvements in student mastery of concepts.

Figure 3 and 4 show consistent improvement across all classes after using PhET Simulation. Students were able to independently explore variables, developing an understanding of Ohm's law and the differences between electrical circuits. This improvement aligns with research by Clarinda et al. (2022), which suggests that the use of virtual laboratories enhances learning motivation and facilitates students' understanding of abstract concepts through a visual approach.

Data Normality Test

The purpose of the data normality test is to determine whether the data is normally distributed. A normality test was conducted to ensure that the learning outcome data were normally distributed before performing parametric analysis. The significance level was set at 0.05. The analysis results showed that all pretest and posttest data had a Sig. Value > 0.05. Thus, the data were found to be normally distributed and met the requirements for parametric statistical analysis.

Furthermore, the data normality results indicated a distribution that met the requirements for parametric analysis. This strengthened the validity of the paired sample t-test results, which showed a significant increase in scores between the pretest and posttest across all classes. This increase is consistent with research by Hermana et al. (2022), which found that virtual laboratories effectively overcome limitations in experimental facilities, thereby supporting the achievement of science learning objectives. Student science literacy in Figure 5 and average normalized gain of the experimental and the replication classes in Figure 6.

The Figure 5 illustrates a significant increase in students' scientific literacy following exposure to interactive media, specifically a virtual laboratory on dynamic electricity. The scientific literacy results indicate that all four classes fell into the "Very Good" category, with average scores ranging from 94.3 to 97.1%. All students demonstrated the following abilities: Identifying scientific phenomena, interpreting simulation data, and Drawing evidence-based conclusions. These findings are supported by Rosli & Ishak (2024), who confirmed that integrating virtual laboratories into science education significantly improves scientific literacy. Meanwhile, Figure 6 shows that there was a significant influence in the experimental and replication classes after being given treatment using Virtual Laboratory in science learning on the Dynamic Electricity. The results of the course, with average normalized gain in the experimental and replication classes, were in the high category in Figure 7-10.

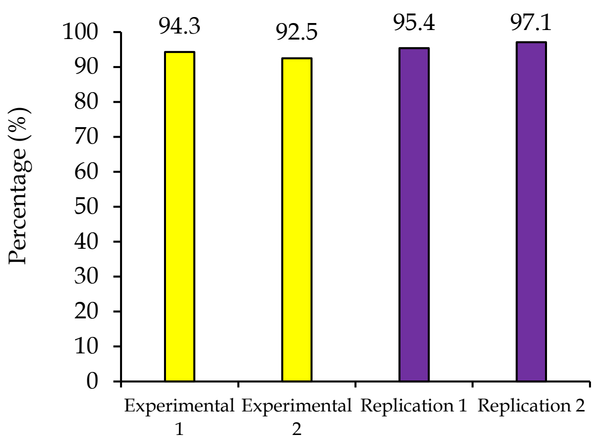

Figure 5. Student science literacy

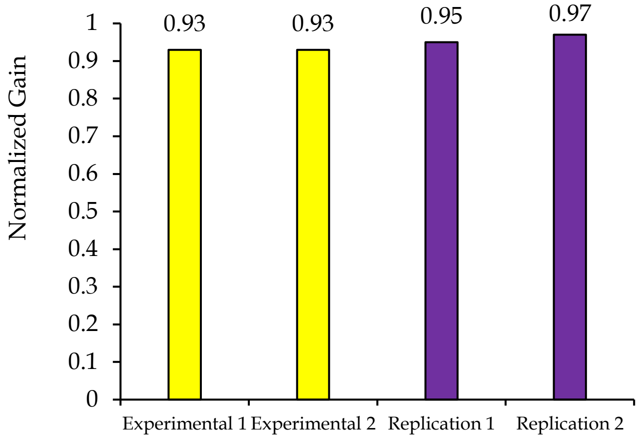

Figure 6. The course average normalized gain of the experimental and the replication classes

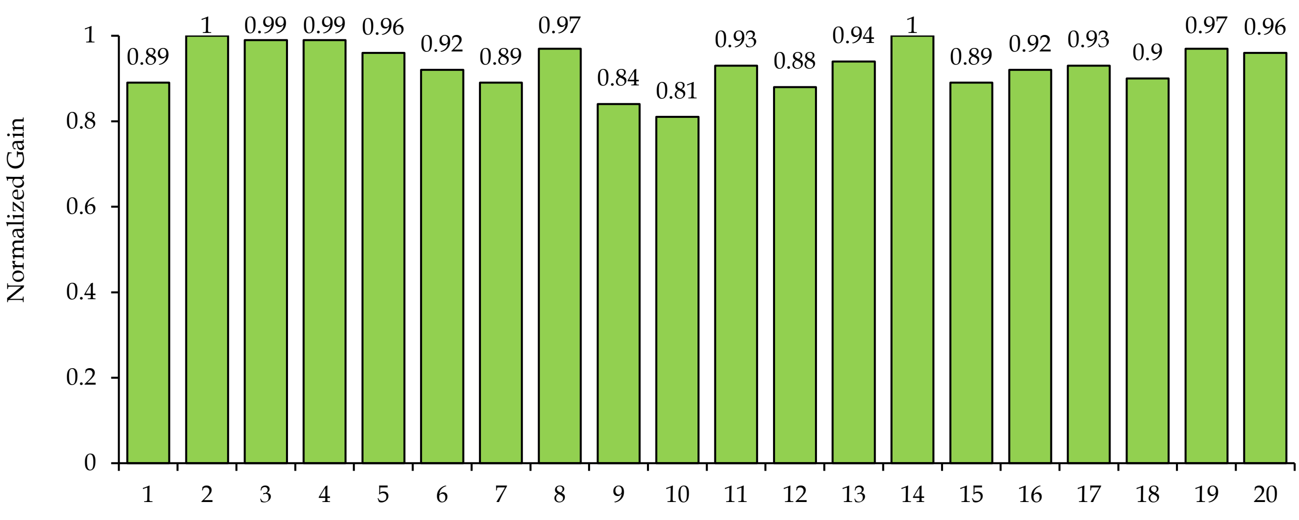

Figure 7. Single student normalized gain experimental 1 (IX-A)

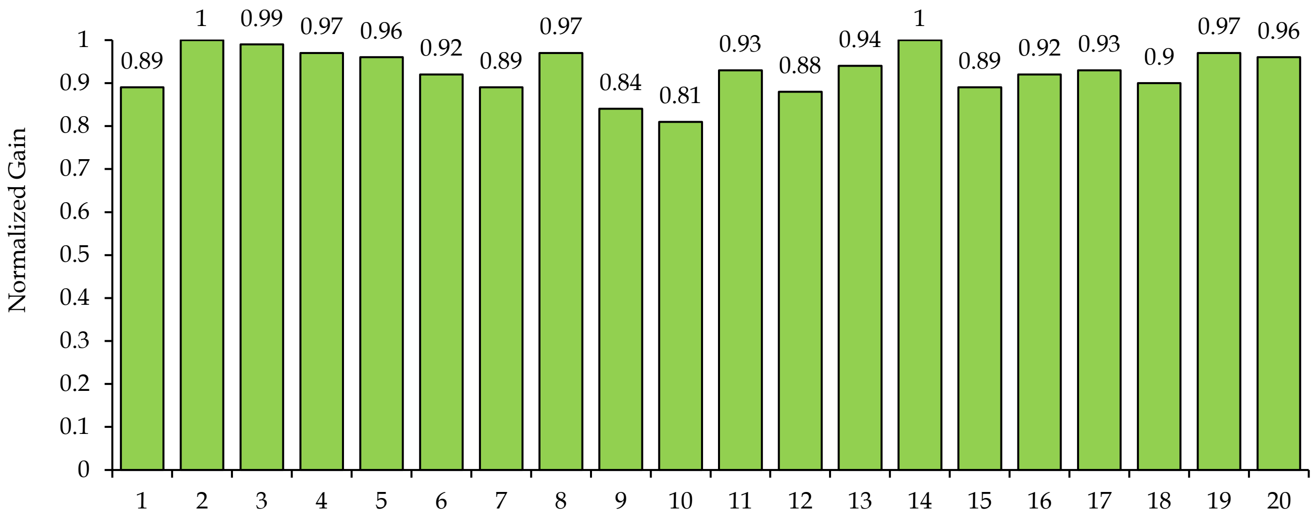

Figure 8. Single student normalized gain experimental 2 (IX-B)

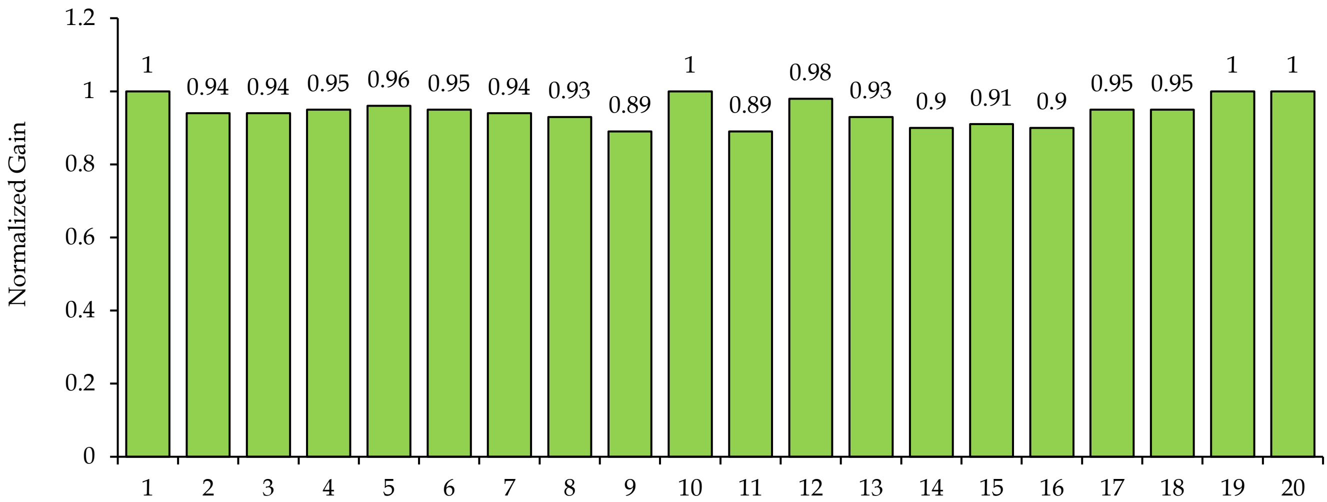

Figure 9. Single student normalized gain replication 1 (IX-B)

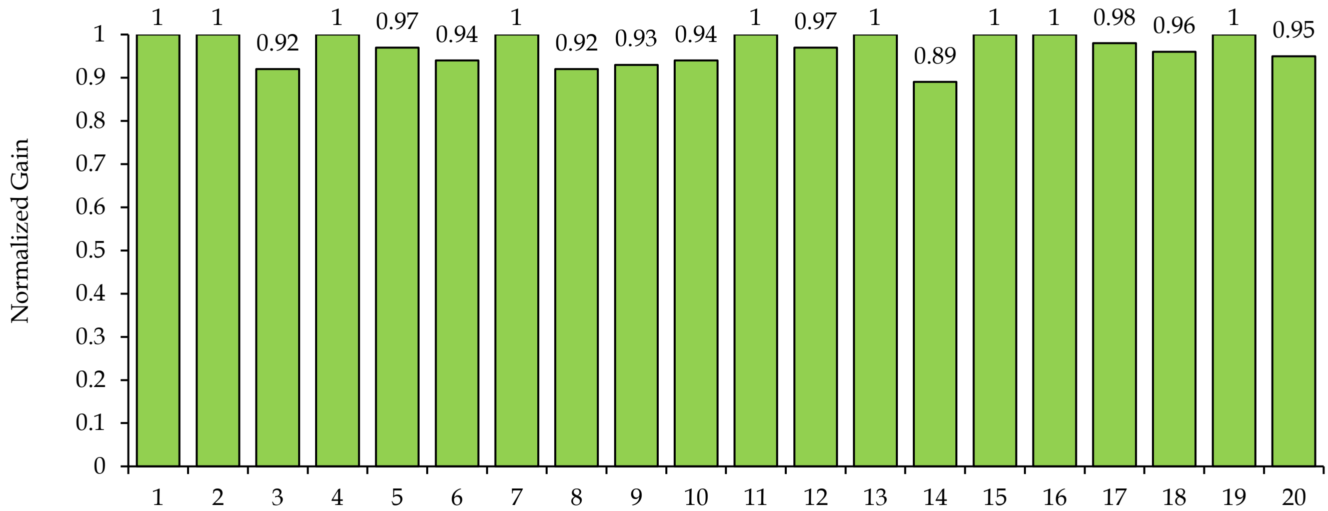

Figure 10. Single student normalized gain replication 2 (IX-A)

Based on Figure 7, the experimental class showed an increase in conceptual understanding. Twenty students in the experimental class fell into the high category. Each student's conceptual understanding improved after being treated with a virtual laboratory in science lessons on Dynamic Electricity. Furthermore, to view the N-gain value for each student in Experimental 2, refer to Figure 8. Based on Figure 8, the experimental class shows an increase in conceptual understanding. In experimental class 2, 20 students were found to be in the high category. Each student's conceptual understanding improved after receiving treatment, utilizing a virtual laboratory in science learning on the topic of Dynamic Electricity.

Based on Figure 9, replication 1 shows an increase in conceptual understanding. In replication 1, 20 students were found to be in the high category. Each student's conceptual understanding improved after being given treatment using a virtual laboratory in science learning on the topic of Dynamic Electricity. Based on Figure 10, replication 2 showed an increase in conceptual understanding. In replication 2, 20 students were found to be in the high category. Each student's conceptual understanding improved after being treated with the virtual laboratory in science learning on Dynamic Electricity.

The N-gain analysis in Figure 6-10 indicates that all classes fell into the high improvement category. This suggests that the Virtual Laboratory is highly effective in enhancing conceptual understanding by allowing students to explore electrical variables independently. These results align with Ismail et al. (2016), who found that the use of STEM-based virtual labs resulted in moderate to high N-gain increases in students' scientific literacy. Thus, the results of this study consistently demonstrate that Virtual Laboratory-based learning has a positive impact on students' conceptual mastery and scientific literacy. These findings support the research of Putri et al. (2021), which reported that inquiry-based virtual laboratories can improve students' conceptual understanding and critical thinking skills in science learning.

Overall, the results of this study confirm that the use of interactive learning media based on Virtual Laboratories is an effective solution to overcome the limitations of laboratory facilities in schools. Students become more active, enthusiastic, and able to connect theoretical concepts with direct visualization through PhET simulations. These results reinforce the findings of Putri et al. (2021), who stated that virtual simulation-based learning can significantly improve concept mastery and scientific literacy. Furthermore, research by Abdjul et al. (2024) also shows that a virtual laboratory approach assisted by interactive simulations is efficacious in improving scientific literacy and higher-order thinking skills. Thus, Virtual Laboratory learning can be recommended as an alternative medium in science learning, especially in schools with limited physical laboratory facilities.

Conclusion

This study demonstrates that the use of interactive learning media based on Virtual Laboratory through PhET Simulation is efficacious in improving students' mastery of concepts and scientific literacy in the subject of Dynamic Electricity. Pretest and posttest results showed significant improvements in all experimental and replication classes, with the average posttest score falling in the "Very Good" category. Statistical analysis using a paired sample t-test yielded a significance value < 0.05 in all classes, indicating a meaningful difference between students' initial and final abilities. Furthermore, the Normalized Gain (N-gain) value was in the high category (0.93–0.97), confirming that Virtual Laboratory-based learning can consistently and efficiently improve conceptual understanding.

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Author Contributions
A.A.A.: conceptualization, writing-original draft preparation, methodology; T.A.: conceptualization, methodology, writing-review and editing; M.Y.: curation, writing-original draft preparation; A.H.O.: methodology; M.: formal analysis; S.: validation.

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Conflicts of Interest
The authors declare no conflict of interest.

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